The economics of tidal stream energy: a spatial approach

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Que la presente memoria titulada “The economics of tidal stream energy: a spatial approach” ha sido realizada por Dña. Ángela Vázquez Álvarez bajo nuestra supervisión y cumple los requisitos establecidos para optar al Grado de Doctor y la Mención Internacional.

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Abstract

So far, the economic assessments of tidal stream energy have been conducted from a sectorial, spatially dimensionless point of view; or in other words, on the basis of mean values obtained as representative of the average across the tidal industry. However, as this marine technology progresses, such assessments will need to be performed on a per-project basis, which inevitably requires the consideration of site-related variables: from the tidal resource to the local topography and accessibility. With this in view, this thesis develops a new methodology to include the spatial dimension into the economic analysis of tidal stream energy projects, and more specifically into the LCOE, in a continuous manner – thereby allowing for macro-micro linkages: impacts of a project over an entire region and *vice versa*. The methodology is materialised in the form of a new *ad hoc* tool and illustrated through a case study in the Bristol Channel and Severn Estuary (UK), a region with one of the greatest potentials for tidal power development in the world. As a result, spatial cost patterns over the study domain, together with environmental and socioeconomic constraints for project deployment are showed. They constitute the basis on which informed decisions on public and private funding allocation should be taken, for a further sustainable development of tidal stream energy hotspots and an integrated coastal management of the regions of interest.

Keywords: Methodology; Tidal stream energy; Levelised Cost of Energy; Spatial economics; Sustainable development.

Resumen

Hasta el momento, las evaluaciones económicas de la energía de las corrientes de marea se han llevado a cabo desde una perspectiva sectorial, sin tener en cuenta el espacio; o, dicho de otro modo, en base a valores medios obtenidos como representativos del sector mareomotriz en su conjunto. Sin embargo, a medida que esta tecnología renovable progresa, dichas evaluaciones tendrán que realizarse a nivel de proyectos, lo que inevitablemente requiere de la consideración de variables espacio-dependientes: desde el recurso mareomotriz local hasta la topografía y la accesibilidad de la zona en cuestión. Teniendo esto en consideración, esta tesis desarrolla una nueva metodología para incluir la dimensión espacial en los análisis económicos de proyectos de energía de las corrientes de marea, y más específicamente en el método del coste nivelado, de forma continua – permitiendo, de este modo, relaciones macro-micro: impactos de un proyecto sobre una región y viceversa. La metodología se materializa en forma de una herramienta *ad hoc* y se ilustra mediante un caso de estudio en el Canal de Bristol y Estuario del Severn (UK), región con uno de los mayores potenciales de energía mareomotriz del mundo. Como resultado, se muestra la distribución espacial de costes en la zona de estudio, junto con restricciones de tipo ambiental y socioeconómico. Estos resultados constituyen la base sobre la que se deben tomar decisiones informadas acerca de financiamiento y asignación de recursos públicos y privados, para lograr un desarrollo sostenible y una gestión integrada de zonas costeras de interés mareomotriz.

Palabras clave: Metodología; Energía de las corrientes de marea; Coste nivelado; Economía espacial; Desarrollo sostenible.

Resumo

Até o de agora, as avaliacións económicas da enerxía das correntes de marea leváronse a cabo dende unha perspectiva sectorial, sen ter en conta o espazo; ou, dito doutro xeito, en base a valores medios obtidos como representativos do sector mareomotriz no seu conxunto. Porén, a medida que esta tecnoloxía renovable progresa, ditas avaliacións terán que levarse a cabo a nivel de proxectos, o que inevitablemente require da consideración de variables espazo-dependentes: dende o recurso local das correntes de marea ata a topografía e accesibilidade da zona en cuestión. Tendo isto en consideración, esta tese desenvolve unha nova metodoloxía para incluír a dimensión espacial nos análises económicos de proxectos de enerxía das correntes de marea, e máis especificamente no método do costo nivelado, de maneira continua – permitindo, de este xeito, relacións macro-micro: impactos de un proxecto sobre una rexión e viceversa. A metodoloxía materialízase en forma dunha ferramenta *ad hoc* e ilústrase mediante un caso de estudo no Canal de Bristol e Estuario do Severn (UK), rexión con un dos maiores potenciais de enerxía das mareas do mundo. Como resultado, móstrase a distribución espacial dos costos na zona de estudo, xunto con restricións de tipo ambiental e socioeconómico. Estes resultados constitúen a base sobre a que se deben tomar decisións informadas acerca do financiamento e asignación de recursos públicos e privados, para lograr un desenvolvemento sustentable e unha xestión integrada de zonas costeiras de interese mareomotriz.

Palabras chave: Metodoloxía; Enerxía das correntes de marea; Coste nivelado; Economía espacial; Desenvolvemento sustentable.

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Symbols and abbreviations

Symbols

A	turbine swept area [m^2]
A_i	total swept area per grid cell i [m^2]
A_f	availability factor
c	salinity or temperature (transported substance)
C_C	cable costs
C_D	drag coefficient
C_f	capacity factor
C_F	cost of foundations
C_G	grid connection costs
C_i	capital cost category
C_I	installation costs
C_p	power coefficient
C_R	rotor costs
C_{2D}	Chézy coefficient
d	local water depth [m]
D	diameter [m]
D_h	horizontal eddy diffusivity [m^2 s^{-1}]
E_t	annual energy output
f	Coriolis parameter
g	gravitational acceleration [m s^{-2}]
L	cable length [km]
n	Manning coefficient
n_i	number of turbines of a tidal farm

O_t	electrical output in year t [kWh]
P_E	price of electricity
P_i	available power density at grid cell i [kW m^{-2}]
P_r	rated power [MW]
Q	intensity of mass sources per unit area [m^2 s^{-1}]
r	discount rate
R	source term per unit area
R^2	correlation coefficient
t	time
t_i	time instant [s]
T	project lifetime [years]
U	vertically integrated eastward component of the flow velocity [m s^{-1}]
v	flow velocity [m s^{-1}]
v_{ci}	cut-in velocity [m s^{-1}]
v_{co}	cut-off velocity [m s^{-1}]
v_r	rated velocity [m s^{-1}]
V	vertically integrated northward component of the flow velocity [ms^{-1}]
V_c	volume of control
ζ	water level [m]
η	efficiency
λ_d	first order decay process
λ_i	percentage of participation on the total amount of capital costs
π	pi
ρ	seawater density [kg m^{-3}]
ρ_0	water reference density [kg m^{-3}]
ρ'	anomaly density [kg m^{-3}]
τ_b	shear stress at the bottom [N m^{-2}]
τ_s	shear stress at the surface [N m^{-2}]
U_h	kinematic horizontal eddy viscosity [m^2 s^{-1}]

Abbreviations

AED	Annual Energy Density
AEP	Annual Energy Production

BODC	British Oceanographic Data Centre
CAPEX	CAPital EXpenditures
FIT	Feed-In Tariff
GBP	British Pound
GEBCO	GEneral Bathymetric Chart of the Oceans
GIS	Geographic Information System
HAT	Horizontal Axis Turbine
ICZM	Integrated Coastal Zone Management
IF	Impact Factor
LAT	Lowest Astronomical Tide
LCOE	Levelised Cost Of Energy
LCaOE	Levelised Capital cost Of Energy
MATLAB	MATrix LABoratory
MoD	Ministry of Defence
MSP	Marine Spatial Planning
OPEX	OPerational EXpenditures
PTO	Power Take Off
PV	Present Value
RMSE	Root Mean Square Deviation
ROC	Renewable Obligation Certificate
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
SW	South West
TEC	Tidal Energy Converter
UK	United Kingdom

I

Introduction

Introduction

1. Motivation and scope of the thesis

Tidal stream energy is at the centre of global efforts towards sustainability. As evidence are the numerous international debates and research projects devoted to this renewable technology over the last decades – the resultant body of knowledge underpinning the commercial realisation of the tidal industry. Nevertheless, the tidal technology readiness gap that has been steadily narrowed is to be eventually closed by the optimal allocation of both public and private funding (Vazquez *et al.*, 2015), for which ex-ante economic assessments are of major importance.

So far, such assessments have been mainly performed on a per-cost-of-energy basis, and in particular using the Levelised Cost Of Energy (LCOE) as the preferred financial metric (Astariz *et al.*, 2015; Vazquez and Iglesias, 2016a). This fundamental parameter is defined as the ratio of total lifetime expenses (both capital and operational costs, CAPEX and OPEX, respectively) *versus* expected outputs (the total amount of energy produced), expressed in terms of the present value equivalent, i.e. by discounting future flows of both costs and energy back to the present (IEA, 2005). The interest of this parameter lies on the simultaneous consideration of timing, costs and revenues; which delivers an energy price (e.g. € per MWh) for which the Net Present Value (NPV) of an investment is zero, or in other words, the break-even of the investment (Dalton *et al.*, 2015).

As a result of previous LCOE studies, single-point, spatially-dimensionless estimates of the costs of tidal stream energy were obtained, serving as a starting point for cross-technological comparisons and discussions around ancillary supporting mechanisms (e.g. Feed-In Tariffs (FITs) or Renewable Obligation Certificates (ROCs)) and roadmaps for cost reduction. For all their interest, these previous appraisals failed to account for the site dependency of the main LCOE inputs, namely, costs and energy produced. Indeed, the total amount of expenditures related to a given tidal project has been included in the LCOE through cost quotations (i.e. average cost values normalised to the installed capacity, considered to be representative of the average across the tidal industry as a whole) (Dalton *et al*., 2015); while the energy yield has been estimated from the mean power output of a standard reference turbine (typically of 1 MW of installed capacity) over a year (OES, 2015). This lack of reference to spatial considerations, although influenced by the paucity of (confidential) project- or device-specific cost information in the public domain, may be fundamentally explained by a strong inertia in economic modelling and, by extension, in the LCOE approach – which has so far been primarily applied to conventional sources of energy. In this regard, the cost of fuel-based technologies or nuclear plants is barely sensitive to the specific project location within a given area or region, except for their proximity to public infrastructure or raw materials. By contrast, tidal stream energy projects face a significant variation in the tidal resource over small areas, and consequently in the corresponding costs, which are highly dependent on spatial variables such as water depth or distance to the shoreline. As an example, varying operating speed and load, corrosion, sea life, structural stresses induced by local winds, waves and currents, all represent threats to the survivability of tidal stream energy systems, which may need to be compensated with higher capital costs. Furthermore, if a tidal farm is far offshore it may require specific vessels for transporting the tidal stream devices, thus making their installation, operation and maintenance costlier and more challenging than it would be in nearshore locations. On these grounds, it becomes clear that a shift towards the inclusion of the space as a new dimension in the economic assessments of tidal stream energy is urgent, especially if confident decision-making on project – and, by extension, funding – allocation is to be made. In terms of the LCOE, such a shift may not necessarily imply the formulation of a new mathematical expression, which indeed could be analogous to the existing ones, but the application of a different underlying modelling approach.

Thanks to existent numerical modelling tools, in-situ data, or a combination of both, the characterisation of the tidal stream resource has been long performed for a number of areas worldwide (see e.g. Carballo and Iglesias, 2009a; Lewis *et al*., 2015), serving as a proxy for identifying the most economic areas for tidal stream exploitation over a region (Ramos and Iglesias, 2013). Embedding resource assessment results into LCOE modelling would be a plausible first step towards spatial economic valuations, which could further serve to perform detailed, per-project analyses under different scenarios of risk and technology development. As a step further, the formulation of the costs (both CAPEX and OPEX) would be done in terms of spatial variables as well, the LCOE results thus serving to select between two sites of interest, with similar tidal stream resource but different geographical features (water depth, distance to the shoreline, etc.)

The interest of obtaining geographical LCOE values may go beyond the spatially-disaggregated microeconomic modelling itself, which would produce accurate, local cost results. Performed in a continuous manner, such a spatial model would yield a picture of LCOE estimates across a region, which ultimately would set scope for macro-micro linkages. Indeed, it is the optimization of the spatial use in coastal zones (especially due to the virtual presence of socioeconomic competing uses and externalities) what principally drives Integrated Coastal Zone Management (ICZM) and Marine Spatial Planning (MSP) (Varghese *et al*., 2008) – macroeconomic policies in essence. Likewise, the optimal allocation of ancillary supporting mechanisms of public funding requires a stronger basis than single-point LCOE estimates. For these mechanisms are stablished by Governments, and thus at a national level, a picture of costs over a region may help in enhancing a specific interesting, conflict-free tidal hotspot in a deliberate, informed manner – by means of establishing, for example, FITs allowing for grid parity with the LCOE of such a site. All in all, extending the economic analyses beyond the confines of a project may allow for the simultaneous consideration of the three pillars of sustainable development, namely, economy, society and environment.

This thesis induces a paradigm shift in the economic assessments of tidal stream energy projects, by means of a novel methodology in which spatial variables are embedded in the economic modelling, and in particular in the LCOE. This methodology is materialised in a new geospatial tool developed *ad hoc*, which, among other advantages, can be easily updated and combined with other geographical information, thus allowing the estimation of two-dimensional LCOE estimates under socioeconomic and environmental constraints. The result is *de facto* a knowledge integrator, coherently incorporating micro-macro economic connections, which allows for further linkages among the three pillars of sustainable development under a single framework of analysis. The applicability of the proposed model is demonstrated for the case of the Bristol Channel and Severn Estuary (UK) – an area that concentrates one of the highest tidal power potential in the world.

The methodology is developed through a series of research articles, published in peer-reviewed journals, composing the main body of this thesis. Each of them constitutes a fundamental step towards the achievement of the final objective of this work: to make available a feasible and reliable methodology whose implementation in a coastal region provides the required information for sustainable decision-making on tidal stream energy exploitation at a commercial level.

2. Justification of the unity and coherence of the thesis

This thesis is divided into seven chapters as follows. First, the present Chapter (I – *Introduction*) provides a rationale and a general overview of the work. Chapter II (*Objectives*) deals with the general and specific objectives, the latter covering the various aspects of the thesis statement in a logical sequence. The next three chapters (III to V) correspond to original research articles published in peer-reviewed journals, which constitute the main body of this work. Each of them systematically addresses one of the three specific objectives – which in turn leads to the achievement of the general objective, and provides coherence and unity to this thesis.

In Chapter III – *LCOE (levelised cost of energy) mapping: A new geospatial tool for tidal stream energy*, a methodology for the economic assessments of tidal stream energy projects is presented. As a novelty, it consists in embedding results pertaining to tidal stream resource assessments into a financial metric, and in particular the LCOE, thereby allowing the extension of this costing metric to the spatial dimension. The methodology is materialised in a new MATLAB-based tool, designed *ad hoc*, and illustrated through a case study in the Bristol Channel and Severn Estuary (UK), for which the first spatial distribution of LCOE for tidal stream energy is obtained. Then, further capabilities of the tool are investigated, and more specifically, a sensitivity analysis to LCOE input parameters is performed. This chapter has been published in *Energy* in 2015, a journal indexed in the Journal Citation Reports with an impact factor (IF) of 4.292 (year 2015).

In Chapter IV – *Capital costs in tidal stream energy projects – A spatial approach*, the methodology previously developed is extended to include other spatial inputs in the LCOE than the site-specific tidal stream energy resource. In particular, a new formula for the CAPEX estimation is proposed, accounting for the dependency of this cost to site-specific project variables, such as water depth or distance to the shoreline. Likewise, the MATLAB-based tool is also extended so as to perform the spatial distribution of capital costs over the same region (Bristol Channel and Severn Estuary). The relationship between the spatial distribution of CAPEX with the LCOE is further investigated, together with its applicability in spatial planning and optimal project allocation. This chapter has also been published in *Energy* in 2016, a journal indexed in the Journal Citation Reports with an IF of 4.292 (year 2015).

In Chapter V – *A holistic method for selecting tidal stream energy hotspots under technical, economic and functional constraints*, the aforementioned methodology is fully developed to include other geographical information, such as environmental and socioeconomic constraints that could prevent the materialisation of a tidal stream energy project at a given location. Implemented in the same region (Bristol Channel and Severn Estuary), the importance of combining economic, societal and environmental information for sustainable decision-making on tidal stream energy deployment is further investigated, together with virtual macro-micro linkages, e.g. the role of selecting tidal stream hotspots (conflict-free and economical areas) in Integrated Coastal Zone Management (ICZM), Marine Spatial Planning (MSP) and the optimal allocation of public funding. This chapter has been published in *Energy Conversion and Management* in 2016 (IF=4.801, year 2015).

It is clear, therefore, that the original research articles composing the main body of this thesis are profoundly connected, which results in a thesis with internal coherence from both the thematic and methodological points of view.

Chapter VI – *General discussion* – presents an overall discussion of the results obtained in the preceding chapters (Chapters III to V), putting them into a wider, academic perspective, thereby ensuring the reader's understanding of the total contribution to research that the compiled articles represent. Finally, Chapter VII – *Conclusions*, summarises the main contributions and findings of the thesis as a whole, states the significance of the present work and gives recommendations for future research.

II

Objectives

Objectives

The general objective of the present thesis is twofold: (i) to develop a comprehensive methodology allowing the inclusion of spatial information in economic structures, such as the Levelised Cost Of Energy (LCOE), so as to improve the quality of the results used in tidal stream energy planning and funding allocation; and (ii) to implement it across a region of interest. For attaining this general objective, the following specific objectives, logically sequenced, are established – each of them corresponding to a publication in a peer-reviewed journal which constitute the main body of this work:

(i). To develop and implement in a coastal region of interest a methodology coupling a standard LCOE model with tidal stream performance data from a Navier-Stokes solver, allowing the reliable computation of the cost of energy produced at any site within the study domain.

Tasks involved: to develop a methodology whose implementation in a coastal region provides the spatial distribution of the LCOE for tidal stream energy projects deployed therein; to implement the methodology in the Bristol Channel and Severn Estuary (UK) by means of a MATLAB-based tool designed *ad hoc*; to analyse through a case study the importance of properly including the spatial dimension in LCOE-based economic assessments; to further perform a sensitivity analysis to various LCOE inputs, thereby making short- and long-term cost predictions.

(ii). To extend the methodology defined in (i) so as to consider the spatial variation of the capital costs (LCOE input parameter) and to implement it to the same coastal region.

Tasks involved: to extend the methodology defined in (i) so as to generate the spatial distribution of capital costs at any location of interest; to adapt the computer application developed in (i) to the new cost formulation; to identify through a case study potential tidal stream sites on the basis of economic suitability and project feasibility; to investigate the role of site-specific results in Marine Spatial Planning (MSP) over the studied region.

(iii). To further extend the methodology developed in (i) and (ii) to account for other spatial information (such as overlapping socioeconomic activities and competing uses over the same coastal region), thereby allowing for investigating macro-micro linkages across the study domain.

Tasks involved: to adapt the methodology previously defined to account for other spatial variables, in particular the presence of competing uses; to implement it in the same location, thereby identifying tidal stream hotspots – conflict-free and economical areas – for project deployment over the studied domain; to establish a relationship between the microeconomic results and macroeconomic policies such as Integrated Coastal Zone Management (ICZM) or public funding allocation.

III

LCOE (levelised cost of energy) mapping: A new geospatial tool for tidal stream energy

A. Vazquez and G. Iglesias

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IV

Capital costs in tidal stream energy projects – A spatial approach

A. Vazquez and G. Iglesias

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V

A holistic method for selecting tidal stream energy hotspots under technical, economic and functional constraints

A. Vazquez and G. Iglesias

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VI

General discussion

General discussion

This thesis develops a holistic methodology for the spatial economic assessment of tidal stream energy projects, thereby providing the elements for making optimal decisions pertaining the allocation of a tidal farm within a coastal region of interest. The methodology, materialised in a new MATLAB-based tool and implemented in the Bristol Channel and Severn Estuary (UK), was developed in a logical sequence of three main steps, each corresponding to a different chapter.

Chapter III – ***LCOE (levelised cost of energy) mapping: A new geospatial tool for tidal stream energy*** presents the first LCOE spatial assessment for tidal stream energy, as a result of obtaining and embedding tidal resource assessment data (varying spatially) into a standard LCOE analysis.

As a first step, the available tidal stream resource over the study area is estimated through numerical modelling. In particular, a finite-difference code solving both the Navier-Stokes and transport equations (the Delft 3D-FLOW model) is used. To implement the model, the bathymetry is obtained from the GEneral Bathymetric Chart of the Oceans (GEBCO) and interpolated into a Cartesian numerical grid covering the study domain: the Bristol Channel and Severn Estuary (UK), extending from the mouth of the River Severn to the Celtic Sea, with the open ocean boundary between St Govan's Head and Trevose Head (Fig.1, Chapter V). The resolution of this grid is set at 500 m, on the basis of a thorough analysis of the bathymetry and the consideration of previous works, which used a similar resolution to investigate the hydrodynamics of the study area showing its appropriateness for an accurate characterisation of the tidal resource (e.g. Ahmadian and Falconer, 2012). As a result, a total number of 35,246 grid cells (target analysis points) are generated.

After running the model for a 50-day period (forced with a Dirichlet boundary condition, with the sea water level prescribed as a function of time using the 9 major tidal harmonics) and validating it (by comparing the model predictions with observations of tidal levels and current velocities at different points over the study domain), a number of parameters are obtained at each grid cell – the time series of depth-averaged velocities through a tidal cycle being of major interest for the purposes of this study. By means of a new tool (MATLAB-based), designed *ad hoc* and capable of accessing to the numerical model results, such velocity series are used to calculate the spatial distribution of the tidal power density, whose numerical integration ultimately yields the energy density available at each bin, or in other words, a resource map of the study area.

This resource map is the basis on which a performance assessment of tidal stream turbines can be conducted (Ramos and Iglesias, 2013), thereby delivering an estimation of the amount of energy that a given tidal farm can produce – a key input for an economic assessment and, in particular, for a LCOE-based one. Therefore, as a next step, a farm projection module is integrated in the aforementioned tool. Thereby, the user is allowed to introduce the main technical specifications of a concrete tidal turbine (used as reference for the study) and, in particular, values of the power coefficient (C_p), the cut-in, rated, and cut-off velocities (v_{ci}, v_r, and v_{co}, respectively), along with the diameter (D) and inter-device spacing within the farm. It is designed (in principle) to automatically calculate the farm size as the maximum amount of turbines that each grid cell could accommodate, and on this basis, to obtain the total swept area and installed power of each farm. Combining technology and site resource data delivers the energy output (potential electrical power production) for each bin. For illustration purposes, a Horizontal Axis Turbine (HAT) with a single 16 m rotor diameter is used, based on the grid-connected prototype turbine (the Seagen-S 600 kW), which deployment in Strangford Narrows (UK) made available data on the power curve, used as well in the present study. Also, an inter-device spacing of 5D is chosen (Ramos *et al*., 2013).

Then, the (spatially varying) energy output thus obtained is embedded into a standard LCOE formula, further complemented with financial data. In particular, the user is allowed to choose the preferred cost quotations (on a per MW basis), for both the capital and operational expenditures (CAPEX and OPEX, respectively), among those available for the tidal stream sector at different stages of development (pre-demonstration, demonstration and commercialisation). From these quotations, the tool automatically calculates the CAPEX, OPEX and the total cost by considering a P_r equal to the rated power of the assessed device (0.6 MW for the SeaGen turbine). The LCOE is finally computed by discounting both costs and energy flows over the lifetime of the installation (T), using a given discount rate (r). By default, T and r are set to 20 years and 10% (respectively) on the basis of the available literature (see Vazquez and Iglesias, 2016a), but could be easily updated on new findings. As a result, the first spatial distribution of the tidal stream cost is obtained in a complete, yet compact, form for the whole region of interest: the LCOE map.

In light of the results, LCOE values of the same order of magnitude of those estimated for the offshore wind sector (around £0.10 per kWh) are found in specific sites with very good tidal resource, e.g. off Barry (on the north coast of the Bristol Channel). Besides, approximately one third of the domain is associated with LCOE values in the range of the strike price considered as the minimum requirement to provide adequate return for investors over a 20-year period and to maintain momentum in the tidal stream energy sector (£0.28-£0.30 per kWh). Furthermore, cost values in line with Feed-In Tariffs (FITs) proposed for the UK solar sector (£0.55 per kWh) are found for approximately half of the domain. Herein, grid parity would be attained, provided that the same level of FITs is realised for the tidal stream sector (Vazquez and Iglesias, 2016a).

Further capabilities of the proposed methodology, which go far beyond the results themselves, are further investigated in this chapter by means of a comparison with the traditional, spatially-dimensionless approach and a sensitivity analysis. The former shows a better performance of the LCOE mapping tool, demonstrating the all-importance spatial and temporal variability of the tidal stream resource for an economic assessment. The sensitivity analysis reveals that the area of economic interest (LCOE < £0.30 per kWh) could be extended by improving the scenarios of analysis, in particular turbines with higher efficiencies and lower cost quotations (referred to a commercial, instead of to a demonstration stage of development), the last one having a greater bearing in cost reductions. Sensitivity results serve, as well, as a basis to make short- and long-term predictions.

For all the interest of the work developed in Chapter III – in which the first spatial economic analysis (through the LCOE) for tidal stream energy is shown – scope for some improvements was identified. On the one hand, the proposed approach restricts the investigation to a given tidal stream turbine, for which the main parameters are introduced by the user. Provided that the developers of a certain turbine are seeking the best and most economical place to install it (alone or as part of an array) across a region, our approach would be very useful, for it also excludes the areas where bathymetric constraints may restrict the operation of such a turbine. However, if the purpose is to study a region as a whole, for the best management of its resources and space, then the potential realisation of the tidal resource should be considered at all the bins, by using different rotor sizes (each satisfying the bathymetric constraints of the site in question). On the other hand, the proposed model works with cost quotations for the estimation of CAPEX and OPEX. This is considered a convenient costing method in general, especially given the paucity of (confidential) project- or device-specific cost information in the public domain (Dalton *et al*., 2015), and indeed it has been used in a number of previous studies (e.g. Allan *et al*., 2012; Astariz *et al*., 2015). Nevertheless, it may narrow the assessment to the maximum of accounting for the cost sensitiveness to different stages of development (pre-demonstration, demonstration and commercial), thus failing to capture the dependency of cost quotations to spatial variables such as water depth or distance to the shoreline – which have been proved to have a bearing on the economics of other marine renewables (e.g. offshore wind energy) (Serrano *et al*., 2011).

On these grounds, the proposed methodology is extended in Chapter IV – ***Capital costs in tidal stream energy projects – A spatial approach****,* and implemented in the same region (the Bristol Channel and Severn Estuary). In the new version, the spatial distribution of energy output across the domain keeps on being a key parameter for delivering the LCOE geographically, and it is obtained through the same procedure than in Chapter III. However, the designed tool is improved so that the turbine diameter (*D*) is automatically calculated to satisfy water depth constraints at each bin. In particular, *D* is obtained as the 70% of the Lowest Astronomical Tide (LAT) at each grid cell (in meters), following the recommendations of previous studies (e.g. Bryden *et al*., 1998). Also, in accordance with Chapter III, the value of *D* is taken into consideration to calculate the size of the tidal farm for each bin (obtained on the basis of the maximum number of turbines that each cell could accommodate with a given device-spacing). For the case study in Chapter IV, a lateral spacing of 5*D* is maintained, but the longitudinal spacing is upgraded to 10*D*, on the basis of a newer study on tidal stream technologies (Royal HaskoningDHV, 2015). From the size of the installation at each grid cell, a total swept area for each farm is obtained, and the electrical power output is delivered spatially.

As regard the costs, Chapter IV centres on re-formulating the estimation of CAPEX to encompass spatial variables. The decision to focus on this parameter is underpinned by several key aspects. First and foremost, capital costs are vital elements of the overall and relative economics of electricity technologies. Actually, they represent about the 70% of the LCOE of tidal stream energy while the remaining percentage corresponds to OPEX. It is also of importance that they are costs incurred before the tidal farm starts operating, which compromises a debt that has to be paid back during the lifetime of the installation, expected at 20 years. Thus the timescale for achieving a return on these capital investments is long and surrounded by uncertainties over market regulations and prices – inherently volatile. Last but not least, CAPEX could be used as a proxy to estimate the amount of OPEX (WEC, 2013), thereby delivering the total costs to be included in a LCOE analysis.

On this basis, a new formula to calculate CAPEX associated to a tidal stream project is proposed, in which a number of spatial-dependent variables are considered together for the first time, including rotor diameter, rated velocity and distance to the shoreline. Implemented in a MATLAB-based tool capable of importing and processing the values of each of these spatial variables at each bin, the spatial distribution of capital costs over the entire studied domain is computed. These costs are further balanced with the amount of energy produced (obtained by the above-explained procedure), by means of a discounting method that accords well with the LCOE. Default values of 20 years and 10%, for the plant lifetime (T) and discount rate (r), respectively, are maintained for the case study. The parameter thus calculated, which we call Levelised Capital cost Of Energy (LCaOE), is used as a proxy of the LCOE for some discussion on the case study, for it may represent 70% of the LCOE.

From the spatial distribution of the LCaOE across the domain, three main areas are distinguished. The so-called Area I, covering approximately one third of the Bristol Channel and Severn Estuary (mostly to the east part), was found to have lower cost values, within the range of the strike price for the sector (which accords well with findings in Chapter III). Such low values are better understood thanks to a number of histograms showing the distributions of the main LCaOE input parameters (Fig.4, Chapter IV), which reveal that Area I is characterised by: mean spring tide velocities in the range 1-2 m s^{-1} (and up to 3 m s^{-1} in some parts), utilizable rotor diameters mostly between 10 m and 25 m (typical of shallow waters), and most frequent cable lengths (distances to shoreline) between 5 km and 10 km (in the range of the greatest part of offshore wind energy parks in the UK (Higgins and Foley, 2014)). Area II, mostly enclosed between Area I and a virtual vertical line connecting the Swansea Bay area and Ilfracombe, is classified as potentially viable, provided that new designs of tidal stream converters are developed, capable of harnessing lower velocities (spring peak speeds around 1 m s^{-1}), and accessing deeper waters (realizable rotor diameters around 20 m) further to the shoreline (up to 20 km). Area III corresponds to the west part of the map, facing onto the open Atlantic Ocean. The lower values of spring tidal velocities (below 1 m s^{-1}), challenging water depths and long distances to points of grid connection (50 m and 35 km , respectively), excludes Area III from the economical tidal stream energy sites, for it shows spatial costs over the highest range of capital costs estimated for the tidal sector (above £0.42 per kWh). Nevertheless, this area could be used for other purposes, such as the exploitation of other renewable energies (e.g. offshore wind energy). Indeed, the interest of the Bristol Channel and Severn Estuary, in terms of marine energy resource quality, has brought it to the centre of discussions around an optimal allocation of renewable energy projects and other competing uses across the marine space (Regen SW, 2012).

Thanks to its spatial character, there was scope for extending the methodology far beyond the frontiers of a project or array, thus accounting for project allocation with a wider perspective. This is done in Chapter V – ***A holistic method for selecting tidal stream energy hotspots under technical, economic and functional constraints***, where the methodology is fully developed to combine spatial LCOE modelling with other geographical information on functional constraints.

To estimate the LCOE, the procedure described in Chapter IV is used, but extended to account for OPEX (in accordance with the costing method included in Chapter III). For this purpose, OPEX are embedded in the LCOE structure as a percentage of CAPEX (calculated through the spatial formula proposed in Chapter IV). Thereby, spatial variables are indirectly included in the OPEX estimation as well. After adding up CAPEX and OPEX, total costs and energy produced (obtained through the procedure explained in Chapter IV) are balanced and discounted back 20 years with a rate of 10% (as in previous chapters). As a result, the LCOE is obtained geospatially, as in Chapter III, but now spatial issues such as water depth or distance to the shore line are fully accounted for in the LCOE structure. Resulting LCOE maps show high correlation to water depths, distance to the shoreline and tidal resource. More specifically, the lower the water depths, distance to the shoreline and the higher the tidal energy output, the lower the LCOE for the assessed tidal stream project.

To explore other capabilities of the designed tool, a sensitivity analysis of energy output to device performance, and in particular, to the power coefficient (C_p) is conducted. Device efficiency is one of the main technical barriers preventing the fully exploitation of the available tidal resource, and therefore, improving the power coefficient is one of the targets of research and innovation efforts aiming at reducing the cost of tidal stream energy (Uihlein and Magagna, 2016). The sensitivity analysis shows how increasing the C_p from 0.30 to 0.40 (minimum and maximum range of values expected for marine current devices (Lim and Koh, 2009)), could extend the study areas above 10 GWh per year and 20 GWh year, by a percentage of 26% to 40%, respectively. Then, it should be taken into account that improved device efficiencies could deliver new LCOE distributions across the study domain.

Previous economic results are combined with spatial information on virtual environmental and socioeconomic constraints hampering the full exploitation of tidal stream energy across the Bristol Channel and Sever Estuary (Ashley, 2014) –

a complex hydrodynamic system supporting a wide range of marine habitats, marine communities and economic interests, as well as providing a major sea transport route into the UK heartland. In particular, data regarding shipping traffic intensity, submarine cabling, nearshore land-based electrical substations, coastal Ministry of Defence (MoD) and natural conservation areas are used and interpolated into the model grid. In principle, grid points overlapping any of the previous constraints are given the value “1”, while the rest are codded as “0”. Note that for shipping traffic activity, the “zero-areas” are those with lower density of vessels (less than 40-160 vessels per year). Then, a new module is added to the MATLAB-based tool, consisting of an overlay function capable of accessing simultaneously all the aforementioned spatial data (i.e. LCOE values and constraints reclassified to two binary values), with a view to deliver an overall suitability map. It is worth mentioning that the tool is prepared to be able to relax certain constraints and thus recode some areas, for not all constraints may be automatically excluding. While it is clear that MoD areas are “hard” constraints (preventing a marine energy installation), the existence of cabling and shipping routes are likely to be subject to negotiations on the basis of the characteristics of the tidal farm and thus are considered “soft” constraints. Thanks to this potential relaxation, different scenarios of analysis can be proposed and investigated.

As a result of the implementation of the new model, a number of hotpsots, (economical and conflict-free bins) are depicted over the study domain, setting scope for micro-macroeconomic linkages across the various spheres of sustainable development. Indeed, the LCOE analysis herein presented is not restricted to a micro, per-project level, but considered through the perspective of spatial planning and public management. In other words, economic results are put into context, complemented with valuable environmental and socioeconomic information, which can contribute to reducing the risk of project denial while maximising the chances of project materialization through optimal allocation of public and private funding over the studied region – macroeconomic issues by nature. As an example, results pertaining spatial distribution of costs (presented in this thesis), can serve as a decision criterion towards a narrower delimitation of the optimum areas to install tidal stream energy farms. Then, their actual allocation may largely depend on avoiding conflicts of use and/or promoting access to existing grid infrastructure (spatial information also included in our methodology). In a certain way, it can serve as well to apply comparative assessments, when two or more projects seem to be feasible.

At a higher level, information on these hotspots may be a source of significant concern for governments all over the world, for they are the basis on which optimal public funding is to be established (Vazquez and Iglesias, 2015d). Required financial support can be provided through several instruments, including FITs, which are subsidies per kWh generated paid in the form of guaranteed premium prices, combined with a purchase obligation by the utilities. Therefore, they are costs related to energy production, in well alignment with the approach presented in this work. So, after site-selection through our method, LCOE values could serve as the basis to promote the realisation of a project in a given area from a sustainable perspective, as accounting for economic, but also environmental and socioeconomic concerns.

All in all, the methodology developed throughout Chapters III, IV and V, is a new decision-making tool which, at the disposal of policy makers and investors, can contribute to reducing the economic uncertainties of future tidal energy projects (by increasing the possibilities of acceptance) and to optimising funding allocation. Capable of being applied not only to the studied area but elsewhere (subject only to data availability), the proposed methodology will contribute to the development of the tidal sector as a whole, as its current economic disadvantage is one of the main barriers to commercialisation.

VII

Conclusions

Conclusions

An informed decision-making process, leading to an optimal allocation of both public and private funding, is a cornerstone in the development of the tidal stream sector, and in particular, in its commercial development. Seen through the lens of sustainable development, such decision-making should rely on the simultaneous consideration of three broad categories – economy, environment and society – for which the establishment of macro-micro linkages would be of major interest. Indeed, the challenge for both governments and industry is to find ways to harness tidal currents at an acceptable cost (microeconomic level), while maximising their real economic value (through positive externalities) and balancing the impact on other marine users and economic interests – inherent macroeconomic constraints.

The existing financial paradigm, based on sector-wide data and single-point results, proved to be suboptimal for responding effectively and timely to funding requirements – which are very project-specific at the present stage of development, with tidal stream energy approaching commercial viability. With this in view, the present thesis develops and applies a new methodology in which the economic assessments of tidal stream energy projects are extended to a new dimension: the space. Thus, the aforementioned assessments are not left to a sector-wide perspective, but to a per-project approach, simultaneously being screened on a regional scale in the context of technological advance, environmental management and socioeconomic development. As a result, the presented model is *de facto* a knowledge integrator, coherently incorporating several sectoral models in a single framework of analysis, including resource modelling tools, economic appraisal techniques and integrated coastal management procedures.

The Bristol Channel and Severn Estuary (UK) is the target region chosen to illustrate the capabilities of the new method, materialised in a new MATLAB-based tool. As a result, the first spatial distribution of Levelised Cost Of Energy (LCOE) for tidal stream energy projects is shown and used as a basis to pre-select tidal stream energy hotspots across the study domain. Then, in conjunction with geographical data of a number of constraints (environmental and socioeconomic), a narrower selection of tidal stream energy project sites is conducted, for which the risks of project denial are minimised.

A salient contribution of this thesis is the extension of the state of the art in economic assessments of tidal stream energy projects by including the space as a new dimension in a financial metric, namely, the LCOE. This constitutes a paradigm shift towards an integrated framework of analysis, allowing for micro-macro linkages – for the spatial character of the results is to help in managing the resources of an area of interest and to provide key insights about the level of subsidisation required to maintain momentum in the tidal stream energy sector as a whole. Also, the marine space hosts a number of socioeconomic activities and environmental goods, which integrated in an economic assessment may allow for overlaps within the three spheres of sustainable development (society, environment and economy). The interest of this work goes then beyond the results of the cases of study presented herein, in that the proposed method can be applied to any tidal stream region of interest where similar data are available.

In future works, the functionalities of the developed tool are expected to be extended. In particular, a great effort is currently being done towards the formulation of the operational costs as a function of spatial variables. Besides, the resolution is planned to be improved for the areas covering the selected tidal stream hotspots (through e.g. model nesting) so that a finer estimation of the characteristics of the assessed tidal farm may be conducted. Extending the applicability of the new method to other marine renewable energies is also under consideration, and could be made possible through collaborative research projects. To this aim, the dissemination by means of the publications in the previous chapters and the presentations at scientific conferences is of crucial importance.

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Appendix

Extended abstract (in Spanish)

La energía de las corrientes de marea concentra los esfuerzos globales hacia el desarrollo sostenible. Prueba de ello son los numerosos debates internacionales y proyectos de investigación que se han dedicado a esta tecnología renovable durante las últimas décadas; siendo el cuerpo de conocimiento resultante, el que ha apoyado el camino hacia comercialización de la industria mareomotriz. No obstante, el salto final hacia la comercialización depende de una óptima asignación de financiación pública y privada (Vazquez *et al*., 2015), para lo cual resultan cruciales las evaluaciones económicas *ex-ante*.

Hasta el momento, dichas evaluaciones se han realizado principalmente en base al coste de energía, y en particular, utilizando el coste nivelado o LCOE (del inglés *Levelised Cost Of Energy*) como la métrica financiera preferida (Astariz *et al*., 2015; Vazquez and Iglesias, 2016a). Este parámetro se define como la proporción entre los costes totales (tanto los de capital como los de operación y mantenimiento, CAPEX y OPEX, respectivamente) y los beneficios esperados (la cantidad total de energía producida) a lo largo de la vida útil de un determinado proyecto energético, expresado todo ello en términos del valor presente equivalente; es decir, descontando los flujos futuros de costes y energía hacia el presente (IEA, 2005). El interés de este parámetro recae en la consideración simultanea de tiempo, costes y beneficios; lo que da como resultado un precio de la energía (por ejemplo, € por MWh) para el que el valor presente neto de una inversión es cero o, dicho de otro modo, el punto de equilibrio de dicha inversión (Dalton *et al*., 2015).

A partir de estudios previos basados en el LCOE se han obtenido estimaciones puntuales aisladas, sin dimensión espacial, del coste nivelado de la energía de las corrientes de marea, siendo el punto de partida de comparaciones entre distintas tecnologías y de discusiones en torno a mecanismos de apoyo financiero complementarios (por ejemplo, las primas a las energías renovables o los certificados de energías limpias) y a hojas de rutas para reducir el coste. A pesar de su interés, estas estimaciones previas no capturan la dependencia espacial de las principales variables de entrada del LCOE, es decir, costes y energía producida. De hecho, el total de gastos asociados a un determinado proyecto de energía mareomotriz se han incluido en el LCOE a través de costes prescritos (es decir, valores medios expresados en términos de potencia instalada, considerados como representativos de toda la industria mareomotriz en su conjunto) (Dalton *et al*., 2015); mientras que la energía producida se ha estimado en base a la potencia media de una turbina estándar de referencia (típicamente de 1 MW de potencia instalada) durante un año (OES, 2015). Esta falta de referencia a consideraciones espaciales, aunque influenciada por la escasez de información (confidencial) sobre costes específicos de proyectos o dispositivos de conversión en el dominio público, se explica fundamentalmente por una fuerte inercia existente en el campo de la modelización económica y, por extensión, en el LCOE – hasta el momento aplicado principalmente a las energías convencionales. A este respecto, el coste de las tecnologías fósiles o las plantas nucleares es ligeramente sensible a la localización específica de las instalaciones de aprovechamiento energético dentro de una región dada, a excepción de su proximidad a infraestructuras públicas o materias primas. Por el contrario, los proyectos de energía de las corrientes de marea se enfrentan a una variación significativa en el recurso mareomotriz en pequeñas distancias espaciales, así como en el total de costes asociados, los cuales son altamente dependientes de variables territoriales como la profundidad o la distancia a costa. A modo de ejemplo, la variabilidad en la velocidad y cargas estructurales, corrosión, vida marina, estrés inducido por vientos, olas y corrientes locales, representa una amenaza para la supervivencia de los sistemas sumergidos de conversión de energía de las corrientes de marea, que necesitará ser compensada con costes de capital más elevados. Además, la localización de una instalación de energía de las corrientes de marea a gran distancia de la costa impondría la necesidad de embarcaciones específicas para el transporte de los dispositivos de conversión, dando lugar a costes más elevados y tareas más arriesgadas de instalación, operación y mantenimiento, en comparación con las necesarias para una instalación cercana a la línea de costa. Sobre esta base, resulta evidente la urgencia de un cambio hacia la inclusión del espacio como nueva dimensión de las evaluaciones económicas relacionadas con la energía de las corrientes de marea, especialmente si los procesos de decisión sobre asignación de proyectos – y por extensión, de financiación – se desean realizar de forma fiable. En términos del LCOE, este cambio no implicaría necesariamente la formulación de una nueva expresión matemática, la cual podría incluso ser análoga, sino la aplicación de un enfoque subyacente distinto.

Gracias a las herramientas existentes de modelización numérica, datos in-situ, o una combinación de ambos, la caracterización del recurso de las corrientes de marea se ha venido llevando a cabo en distintas áreas del planeta (véase, por ejemplo, Carballo and Iglesias, 2009a; Lewis *et al*., 2015), sirviendo para identificar de forma indirecta las áreas más económicas para la explotación de la energía de las corrientes de marea dentro de una región (Ramos and Iglesias, 2013). Insertar los resultados de evaluaciones del recurso de las mareas en modelos LCOE podría constituir el primer paso hacia la realización de valoraciones económicas espaciales, que podrían servir, a mayores, para llevar a cabo análisis detallados de proyectos bajo distintos escenarios de riesgo y desarrollo tecnológico. Como siguiente paso, la formulación de los costes (CAPEX y OPEX) se podría hacer también en términos de variables espaciales, de tal modo que los resultados de coste nivelado pudiesen servir para seleccionar una localización entre dos de interés económico, con recurso mareomotriz similar, pero distintas características geográficas (profundidad, distancia a costa, etc.)

La ventaja de combinar valores geográficos de LCOE iría más allá del modelado microeconómico en se per se, que daría lugar a costes locales y exactos de forma desagregada. Llevado a cabo de forma continua, dicho modelado espacial daría lugar a una distribución geográfica de estimaciones de LCOE para toda una región, lo cual podría, en última instancia, sentar las bases para asociaciones macro-micro. De hecho, es precisamente en la optimización del uso del espacio en zonas costeras (especialmente debido a la presencia virtual de otras actividades socioeconómicas y externalidades) de lo que se ocupa la Gestión Integrada de Zonas Costeras (ICZM, del inglés *Integrated Coastal Zone Management*) y la Planificación Espacial Marítima (MSP, del inglés *Marine Spatial Planning*) (Varghese *et al*., 2008) – políticas esencialmente macroeconómicas. De igual modo, la asignación óptima de recursos financieros públicos requiere una base más sólida que la que ofrecen las estimaciones puntuales de coste nivelado existentes. Dado que tales recursos son establecidos por los gobiernos, y por tanto a nivel nacional, disponer de la distribución espacial de costes en una región puede ayudar a promocionar ciertas áreas de interés para la explotación de la energía de las corrientes dentro de la misma – por medio del establecimiento de primas que igualen el LCOE del área en cuestión. En definitiva, extender los análisis económicos más allá de los confines de un proyecto permitiría la consideración simultánea de los tres pilares del desarrollo sostenible: economía, sociedad y medio ambiente.

Esta tesis induce un cambio de paradigma en las evaluaciones económicas de proyectos de energía de las corrientes de marea, por medio de una nueva metodología en la que se insertan variables espaciales en modelos económicos, y en particular en el LCOE. Esta metodología se materializa en una herramienta geoespacial nueva, desarrollada *ad hoc*, la cual, entre otras ventajas, puede ser fácilmente actualizada y combinada con otra información espacial, permitiendo así la estimación de valores de coste nivelado con dos dimensiones bajo restricciones socioeconómicas y ambientales. El resultado es *de facto* un modelo integrador de información, que incorpora conexiones macro-micro económicas de forma coherente, lo que permite a mayores establecer nexos entre los tres pilares del desarrollo sostenible dentro del mismo marco de análisis. La aplicabilidad del modelo propuesto se demuestra para el caso del Canal de Bristol y Estuario del Severn (Reino Unido) – un área que concentra uno de los potenciales de energía mareomotriz más elevados del mundo.

Esta tesis se estructura en siete capítulos, de los cuales los Capítulos III, IV y V corresponden con sendas publicaciones en revistas científicas y constituyen el cuerpo principal de la tesis. En primer lugar, en el Capítulo I – *Introduction*, se detalla la motivación de la tesis en relación a los antecedentes temáticos y metodológicos del campo de estudio de la misma y se proporciona una visión general al presente trabajo, justificando su unidad y coherencia. En el Capítulo II – *Objectives*, se plantean los objetivos general y específicos que se pretenden alcanzar. A continuación, en los Capítulos III – *LCOE (levelised cost of energy) mapping : A new geospatial tool for tidal stream energy*, publicado en *Energy*, IV – *Capital costs in tidal stream energy projects – A spatial approach*, también publicado en *Energy* y V – *A holistic method for selecting tidal stream energy hotspots under technical, economic and functional constraints*, publicado en *Energy Conversion and Management*, se presenta, de forma consecutiva, el desarrollo de la metodología propuesta, así como su implementación en el Canal de Bristol y Estuario del Severn. El Capítulo VI – *General Discussion*, contiene una discusión general común a la tesis, situándola en un contexto más amplio y mostrando la contribución de la misma como un todo. Finalmente, en el Capítulo VII – *Conclusions*, se presentan las principales conclusiones obtenidas, destacando su relevancia para el campo de estudio al que contribuye la tesis, así como las futuras líneas de investigación a desarrollar.

A continuación, se presenta de forma sintética la metodología propuesta, se resumen los aspectos abordados, así como los resultados y principales conclusiones obtenidas.

En el Capítulo III – ***LCOE (levelised cost of energy) mapping : A new geospatial tool for tidal stream energy***, se presenta la primera evaluación espacial de coste nivelado para la energía de las corrientes de marea, como resultado de la obtención, y posterior integración, de datos del recurso mareomotriz en un análisis de LCOE estándar.

En primer lugar, se estima el recurso disponible de energía de las corrientes de marea en el área de estudio (Canal de Bristol y Estuario del Severn), mediante modelización numérica. En particular, se utiliza un modelo de diferencias finitas que resuelve la ecuación de Navier-Stokes y la de transporte (Delft 3D-FLOW). Para implementar este modelo, se obtiene la batimetría del *GEneral Bathymetric Chart of the Oceans* (GEBCO) y se interpola con una malla numérica de tipo cartesiano que cubre toda el área de estudio: el Canal de Bristol y Estuario del Severn, desde la desembocadura del Río Severn hasta el Mar Céltico, estando situada la frontera abierta al océano entre St Govan's Head and Trevose Head (Fig.1, Capítulo V). La resolución de esta malla se fija a 500 m, en base a un extenso análisis de la batimetría y la consideración de estudios previos, los cuales han usado una resolución similar para investigar la hidrodinámica del área de estudio (véase, por ejemplo, Ahmadian and Falconer, 2012), mostrando así su validez para realizar una caracterización del recurso mareomotriz adecuada. Como resultado, se generan 35.246 nodos de malla (puntos objetivo de análisis).

Tras correr el modelo por un periodo de 50 días (forzándolo con una condición de Dirichlet en la frontera abierta, con el nivel de mar expresado en función del tiempo usando los 9 harmónicos principales) y validarlo (comparando las predicciones del mismo con observaciones de niveles de marea y velocidades de corrientes en distintos puntos del área de estudio), se obtienen una serie de parámetros en cada nodo de malla – siendo las series de velocidad durante un ciclo de marea de máxima relevancia para los objetivos del presente estudio. Por medio de una nueva herramienta de MATLAB, diseñada *ad hoc* y capaz de acceder a los resultados del modelo numérico, dichas series de velocidad se usan para calcular la distribución espacial de densidad de potencia, cuya integración numérica proporciona la densidad energética en cada nodo de malla o, dicho de otro modo, un mapa del recurso del área de estudio.

Este mapa del recurso es la base sobre la que se pueden realizar análisis de rendimiento de turbinas mareomotrices (Ramos and Iglesias, 2013), obteniéndose de este modo una estimación de la energía que una determinada instalación mareomotriz podría producir – un input clave para un análisis económico y, en particular, para uno basado en el LCOE. Por tanto, como siguiente paso, se integra en la herramienta un módulo de proyección de una instalación mareomotriz. Por medio del mismo, el usuario puede introducir las características técnicas principales de una turbina mareomotriz específica (utilizada de referente para el estudio) y, en particular, valores del coeficiente de potencia, de las velocidades de trabajo de la misma, del diámetro y del espaciado entre turbinas. La herramienta se ha diseñado, en principio, para que calcule de forma automática el tamaño de la instalación como el máximo número de turbinas que entran en cada nodo, y sobre esta base, obtenga el área total de captura y la potencia instalada de la misma. La combinación de datos de recurso y tecnología de captación da lugar a la obtención de la energía producida en cada nodo de malla. A modo ilustrativo para el caso de estudio, se utiliza una turbina de eje horizontal con un diámetro de 16 m, basada en un prototipo (SeaGen-S 600 kW) conectado a la red en Strangford Narrows (Reino Unido) del que se han obtenido datos de curva de potencia también usados en esta tesis. Por otro lado, el espaciado entre turbinas empleado es de 5 diámetros (Ramos *et al*., 2013).

Posteriormente, la producción energética obtenida (que varía de forma espacial) se introduce en una formula estándar de LCOE, complementada a mayores con datos financieros. En concreto, el usuario puede escoger los costes prescritos de capital y operación y mantenimiento (expresados por MW) que quiere usar para el análisis, de entre los que están disponibles para el sector mareomotriz (a escala de pre-demostración, demostración y comercialización). A partir de estos costes prescritos, la herramienta calcula automáticamente el total de CAPEX, OPEX y suma de costes, considerando una potencia instalada igual a la de la turbina evaluada (0.6 MW para el modelo SeaGen). El LCOE se calcula finalmente descontando los flujos futuros de costes y energía a lo largo de toda la vida útil de la instalación (T) y usando una tasa de descuento (r) determinada. Por defecto, los valores de T y r se fijan en 20 años y 10% (respectivamente) en base a la bibliografía disponible (Vazquez and Iglesias, 2016a), pero podrían modificarse fácilmente para adaptarlos a nuevos hallazgos. Como resultado se obtiene la primera distribución espacial de costes de energía de las corrientes de marea de forma completa, a la vez que compacta, para la región de interés: el *LCOE map*.

A la vista de los resultados, se obtienen valores de coste nivelado del mismo orden de magnitud que los encontrados para el sector eólico marino (sobre £0.10 por kWh) en zonas específicas con un recurso mareomotriz excelente, por ejemplo, frente a la costa de Barry (al norte del Canal de Bristol). Además, aproximadamente un tercio del dominio estudiado está asociado con valores de LCOE del mismo rango del coste nivelado de referencia para proporcionar retornos adecuados a los inversores y crear momento en la industria mareomotriz (£0.28-£0.30 por kWh). A mayores, valores de coste nivelado en línea con las primas propuestas en Reino Unido para el sector solar (£0.55 por kWh) se han encontrado para la mitad del dominio aproximadamente. En este área se podría alcanzar la paridad con los costes de red, si se aplicasen las mismas primas para el sector mareomotriz (Vazquez and Iglesias, 2016a).

A pesar del interés del trabajo desarrollado en el Capítulo III – en el que se presenta el primer análisis económico espacial (basado en el LCOE) para la energía de las corrientes de marea – se han identificado una serie de mejoras posibles. Por un lado, el enfoque propuesto restringe la investigación a una turbina mareomotriz en concreto, de la que el usuario introduce los parámetros técnicos principales. Esto puede resultar de gran utilidad para los desarrolladores de una turbina en concreto, especialmente si están buscando la localización (dentro de una región) más económica para instalarla (sola o como parte de un array), ya que la aplicación que hemos desarrollado excluye además del análisis aquellas áreas en las que no se podría instalar por restricciones batimétricas. Sin embargo, si el objetivo es evaluar una región en su conjunto, para la mejor gestión de sus recursos y espacios, entonces se tienen que tener en cuenta todos los nodos de la malla, y usarse distintos tamaños de turbina en el análisis (cada uno de ellos satisfaciendo las restricciones de espacio correspondientes). Por otro lado, el modelo propuesto trabaja con costes prescritos para estimar el total de CAPEX y OPEX. Este enfoque se considera conveniente debido a la escasez de datos de dominio público, y de hecho se ha aplicado en trabajos previos (por ejemplo, en Allan *et al*., 2012; Astariz *et al*., 2015). No obstante, restringe el análisis a la mera consideración de distintos valores de coste en función de la etapa de desarrollo del sector mareomotriz, despreciando la dependencia de dichos costes a variables espaciales como profundidad o distancia a costa.

En base a lo anterior, la metodología propuesta se completa en el Capítulo IV – ***Capital cost in tidal stream energy – A spatial approach***, y se implementa en la misma región (Canal de Bristol y Estuario del Severn). En la nueva versión, se mantiene la distribución espacial de energía producida como parámetro clave para obtener el coste nivelado de forma geográfica (el cual se calcula siguiendo el mismo procedimiento que el Capítulo III). Sin embargo, la herramienta diseñada se mejora para que calcule el diámetro de la turbina que mejor se ajustaría a la batimetría de cada nodo de malla (siendo éste el 70% del nivel más bajo de marea en el nodo en cuestión). Al igual que en Capítulo III, este valor de diámetro permite obtener el tamaño total de la instalación a evaluar. Para el caso de estudio de este capítulo se utiliza un espaciado entre turbinas lateral de 5 diámetros, mientras que el longitudinal se amplía a 10 diámetros, en base a un nuevo estudio sobre tecnologías mareomotrices (Royal HaskoningDHV, 2015). A partir del tamaño de instalación en cada nodo, se obtiene el área de captación total y, por consiguiente, la distribución espacial de la producción eléctrica.

En relación a los costes, el Capítulo IV se centra en re-formular la estimación de costes de capital para tener en cuenta variables espaciales en la misma. El hecho de centrarnos en los costes de capital responde a una serie de razones, entre ellas, su mayor peso (respecto a los OPEX) en el total de costes y la posibilidad de usarlos como base para estimar los costes de operación y mantenimiento, al igual que se ha hecho en trabajos previos (WEC, 2013).

En base a lo anterior, se propone una nueva fórmula para calcular los costes de capital asociados a una instalación de energía de las corrientes de marea, en la que se consideran por primera vez juntas una serie de variables espaciales, incluido el tamaño del rotor, la velocidad de trabajo de la turbina y la distancia de la misma a la costa. Al implementar esta fórmula en una herramienta de MATLAB, capaz de importar y procesar dichas variables espaciales en cada nodo de la malla, se obtiene la distribución espacial de costes de capital para la zona de estudio. Estos costes se compensan a mayores con la energía producida (obtenida por el procedimiento explicado anteriormente), mediante un método de descuento que se corresponde con el empleado para el cálculo del LCOE. El parámetro resultante de esta compensación, acuñado como coste de capital nivelado (LCaOE del inglés *Levelised Capital cost Of Energy*), se utiliza para hacer una discusión de resultados del caso de estudio.

A partir de la distribución espacial del LCaOE en la región de estudio, se distinguen tres zonas. La denominada Zona I, que cubriría aproximadamente un tercio del Canal de Bristol y el Estuario del Severn (hacia la parte este), tiene los costes más bajos, del orden del considerado punto de equilibrio del sector (lo cual concuerda con los resultados encontrados en el Capítulo III). Estos valores bajos se entienden mejor gracias a los histogramas que muestran las distribuciones de los principales inputs del LCaOE (Fig.4, Capítulo IV), que revelan que la Zona I se caracteriza por: velocidades medias de corrientes en mareas vivas de 1 a 2 m s^{-1} (y hasta 3 m s^{-1} en algunas partes), diámetros de rotor utilizables mayormente entre 10 m y 25 m (típicos de aguas poco profundas), y longitudes de cable más frecuentes (distancias a costa) entre 5 km y 10 km (similares a las de la mayor parte de parques eólicos offshore en Reino Unido (Higgins and Foley, 2014)). La Zona II, confinada mayoritariamente entre la Zona I y una línea imaginaria que conectaría la Bahía de Swansea con la localidad de Ilfracombe, se clasifica como potencialmente viable, siempre y cuando se desarrollen nuevos convertidores de energía de las corrientes de marea capaces de captar velocidades de corriente más bajas, en zonas de aguas más profundas (para diámetros de rotor utilizables en torno a 20 m) y más alejadas de la costa (hasta 20 km). La Zona III se corresponde con la parte oeste del mapa (situada frente al océano Atlántico). Los valores bajos de velocidad de corriente en mareas vivas (por debajo de 1 m s^{-1}), la profundidad de sus aguas (~50 m) y la gran distancia a puntos de conexión potenciales con la red eléctrica existente (35 km), sitúan a esta Zona III fuera de las áreas de interés para la explotación económica de la energía de las corrientes de marea. No obstante, esta zona podría usarse para otros propósitos, como la explotación en ella de otros recursos renovables (por ejemplo, energía eólica marina). De hecho, la importancia del Canal de Bristol y el Estuario del Severn, en términos de calidad de recurso energético marino, lo ha situado en el centro de discusiones en torno a una óptima asignación de proyectos de energía renovable en conjunción con otros usos competitivos del espacio marítimo (Regen SW, 2012).

Gracias a su carácter espacial, ha habido margen para extender la metodología propuesta más allá de las fronteras de un proyecto, aplicando así una perspectiva más amplia en la disposición espacial de los mismos. Esto es lo que se ha hecho en el Capítulo V – ***A holistic method for selecting tidal stream energy hotspots under technical, economic and functional constraints***, en el que se desarrolla completamente la metodología para combinar el modelado espacial del LCOE con otra información geográfica de interés.

Para estimar el LCOE, se usa el mismo procedimiento que en el Capítulo IV, pero se extiende éste para tener en cuenta los costes de operación y mantenimiento (en línea con la propuesta del Capítulo III). Para ello, los OPEX se incluyen en la estructura de cálculo del LCOE como un porcentaje de los CAPEX (obtenidos mediante el método del Capítulo IV). Así, los OPEX incorporan también variables espaciales de forma indirecta. Los resultados de LCOE en forma de mapas muestran una clara correlación con las variables espaciales investigadas. En particular, se puede ver cómo cuanto peor sea el recurso y mayor sean las profundidades y distancias a costa, se obtienen mayores valores de coste nivelado.

Los resultados económicos previos se combinan a continuación con información espacial sobre restricciones de tipo socioeconómico y ambiental que podrían prevenir la materialización de proyectos de energía mareomotriz en el Canal de Bristol y Estuario del Severn (Ashley, 2014) – un sistema hidrodinámico complejo que contiene gran cantidad de hábitats marinos e intereses económicos, a la vez que proporciona la mayor ruta de tráfico marítimo al corazón de Reino Unido. En particular, se utilizan datos de intensidad de tráfico marítimo, cableado submarino, subestaciones eléctricas costeras, zonas de actividad militar y áreas de conservación natural, que se interpolan con la malla empleada para el modelo numérico. En principio, a los nodos de malla que se solapan con alguno de los datos anteriores se les da un valor de “1”, mientras que el resto se codifican con valores “0”. Nótese que, para los datos de tráfico marítimo, las áreas codificadas con un “0” son aquellas cuya densidad de tráfico anual no supera los 40-160 barcos por año. Posteriormente, se añade un módulo a la herramienta de MATLAB que contiene una función capaz de acceder a toda la información espacial citada anteriormente (es decir, resultados de LCOE y restricciones socioeconómicas y ambientales recodificadas con valores binarios), con el fin de que se obtenga un mapa de idoneidad para proyectos de energía de las corrientes de marea.

De este modo, se sientan las bases para establecer relaciones macro-micro económicas a través de las distintas esferas de desarrollo sostenible. De hecho, el análisis de coste nivelado presentado en esta tesis no se reduce al nivel de proyecto (micro), sino que se integra dentro de una perspectiva más amplia de planificación espacial y gestión pública del espacio marino. Dicho de otro modo, los resultados económicos obtenidos se ponen en contexto, ya que son complementados con información muy valiosa sobre actividades socioeconómicas y restricciones ambientales que pueden constituir un riesgo para la aprobación de proyectos, a la vez que maximizan las oportunidades de materialización de los mismos por medio de una óptima asignación de financiación pública y privada – cuestiones macroeconómicas por naturaleza.

Para concluir, la metodología desarrollada en los Capítulos III, IV y V es una nueva herramienta de toma de decisiones que, a disposición de políticos e inversores, puede contribuir a reducir las incertidumbres económicas sobre proyectos de energía de las corrientes de marea futuros y optimizar asignación económica dedicada a los mismos. Además, dado que puede ser aplicada a otras regiones de interés, la metodología propuesta en esta tesis puede contribuir al desarrollo último del sector mareomotriz en su conjunto, ya que la económica es la barrera principal para su comercialización.

En el futuro, se espera extender las funcionalidades de esta metodología. En concreto, se está realizando un gran esfuerzo para formular los costes de operación y mantenimiento en base a variables espaciales. Además, se prevé incrementar la resolución del modelo numérico para las zonas denominadas de interés para la explotación de energía de las corrientes (por ejemplo, por medio de modelos anidados), de tal modo que se pueda hacer una proyección más exacta. También se plantea extender la aplicabilidad del nuevo método a otras energías marinas, lo cual se podría conseguir por medio de proyectos de colaboración con otras áreas de investigación. Para este último fin, resulta clave la difusión de este trabajo por medio de las publicaciones ya efectuadas y la participación en diversas conferencias de ámbito internacional a las que se asistirá.